ARS 42-148
January 1969

UNITED STATES DEPARTMENT OF AGRICULTURE
Agricultural Research Service

RELATION OF FREQUENCY AND LENGTH OF SHAKER STROKE TO THE MECHANICAL HARVESTING OF APPLES[1/]

R. G. Diener, J. H. Levin, and R. T. Whittenberger[2/]

ABSTRACT

Efficient mechanical harvesting of apples is largely dependent on rapid fruit removal, which requires use of proper frequency and stroke.

In this study, a frequency range of 400 to 600 cycles per minute was found to be best for shaking Jonathan apples. On the basis of this frequency range, a shaker stroke of 7 to 8 inches would be necessary to remove all the fruit on the first stroke. The use of shorter strokes and fatigue failure over longer shaking periods is discussed as well as the efficiency of the limb in transmitting the stroke from the clamp location to the end of the limb.

The study also gives design values for the unbalance shaker mass and boom mass for inertia shakers used on conventional limbs and discusses the effect of the crank arm-connecting rod ratio on acceleration and stroke.

1/ Agricultural Engineering Research Division and Eastern Utilization Research and Development Division, Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the Agricultural Engineering Department, Michigan State University.

2/ Assistant professor, Department of Agricultural Engineering, West Virginia University, Morgantown; Leader, Fruit and Vegetable Harvesting Investigations Group, Agricultural Engineering Research Division, ARS, USDA, Agricultural Engineering Department, Michigan State University, East Lansing; and research biochemist, Eastern Utilization Research and Development Division, ARS, USDA, Philadelphia, Pa.

INTRODUCTION AND OBJECTIVES

In 1967 over 110,000 bushels of apples for processing were harvested mechanically in Michigan and New York. When proper padding and deceleration strips were used, the quality of mechanically picked fruit approximated that of handpicked fruit for processing.

With the shortage of hand labor and the coming availability of lower cost apple harvesters, the harvesting of processing apples will be almost completely mechanized within a few years.

The efficiency of these mechanical harvesters depends on minimization of shaking time by use of proper stroke and frequency. Previous studies on trellis-trained apple trees(3)[3/] showed that pendulum, tilting, bouncing(7), and rotational modes of vibration were in the frequency range of 80 to 450 cycles per minute. The rotational mode, which occurred at about 450 c.p.m. was the most effective for fruit detachment but even with a 2-inch stroke, shaking time was excessive.

Although larger displacement of the fruit occurred at lower frequency modes, the acceleration forces of the fruit were too small for effective detachment. Due to vibration isolation of small limbs, higher frequencies up to 1,000 c.p.m. were largely ineffective for fruit removal even with a 2-inch stroke. In addition, excessive leaf fall and limb damage occurred at higher frequencies.

Vibration and tree geometry are not the same in large, standard trees and trellis-trained trees. For this reason, a study of stroke, frequency, and fruit detachment efficiency was made in commercial orchards in southwest Michigan in the fall of 1967. Tests were conducted on standard size Jonathan apple trees pruned for mechanical harvesting that had three to four scaffold branches and open centers.

Specific objectives of the study were:

1. To determine the shaking frequency that gives the highest detachment efficiency.

2. To determine the required shaker stroke in terms of optimum frequency, pull force, and limb efficiency.

3. To determine the mass and crank throw necessary for inertia apple shakers based on the limb and stroke requirements.

3/ Underscored numbers in parentheses refer to Literature Cited at end of report.

PROCEDURE

For the field tests, three shakers were used: (1) An inertia shaker (cherry shaker) shown in figure 1; (2) a larger inertia shaker of the same design; and (3) a positive displacement shaker.

Figure 1. General view of equipment used in shaker frequency tests showing the limb shaker, measurement of stroke, low profile catching frame, and some of the electronic equipment.

Measurement of Frequency

Shaker frequency was measured with a power instrument G 813 magnetic pickup with a 60-tooth gear on the shaker crankshaft. Frequency was read on a four-digit Hewlett Packard frequency counter in second gate time. Frequency was also calculated from the acceleration strip chart recordings. This method was accurate to within 3 percent and was much simpler than using the frequency counter.

Measurement of Frequency Efficiency

Shaking time at each frequency was limited to one short burst of 3 to 4 seconds duration. Shaking was stopped immediately when apples stopped falling from the limb. The fruit was collected on an experimental low-profile catching frame shown in figure 1. Counts were made of the fruit removed and fruit left on the limb and of the number of spurs attached to the harvested apples.

Stroke Measurement

Stroke was measured by drawing a felt marker across a board attached to the shaker boom as shown in figure 2. The felt marker was guided by an adjustable shaft on an aluminum tripod as shown in figure 2. This simple technique worked very well.

Figure 2. Measurement of the stroke by drawing a marker across a board attached to the boom.

Limb Transmission Efficiency Measurement

In this study, the stroke at the end of the limb was compared to the stroke at the clamp by the use of accelerometers at these locations. The voltage output was amplified by amplifiers and differential amplifiers. The two acceleration curves were recorded by a two-channel oscillograph shown in figure 3.

Figure 3. Instrumentation used in field tests showing frequency counter, preamplifier, and strip chart recorder.

Phase Angle Between Boom and Eccentric Mass

The phase angle between the boom and the eccentric mass, Mu, is needed for design calculations of shaker mass and stroke. This angle was measured using accelerometers placed on the boom and shaker handle. A calibration curve was also run by placing both accelerometers together on the boom. This compensated for electronic phase shifting of the instruments.

RESULTS

Optimum Frequency

The best frequency for removal of Jonathan apples was between 400 and 600 c.p.m. as shown in table 1 and figure 4. Values are given in percent of fruit detached per second of shake to include the times required to clear each individual limb in the efficiency rating. Average shaking times for all limbs was 4.1 seconds with 85-percent removal and 25 strokes.

Measurement of the Stroke

The stroke for all tests was about 1 inch. Sample measurements using the clipboard on the boom are shown in figure 5 for an inertia shaker. In an inertia shaker operation the inertia force of both the shaker and the limb increase with frequency so that the stroke remains constant. Values of stroke are also shown in table 1. The shapes of the displacement curves are identical with those later shown for acceleration.

In the curve for 100 c.p.m. (fig. 5), the motion is roughly sinusoidal. The flat spots at the beginning of the forward motion and at the end of the rearward stroke are due to motion of the boom perpendicular to the direction of the shake.

Effect of High and Low Frequencies

Below 400 c.p.m. the acceleration was generally too low to provide sufficient force to remove the fruit. First resonance of the limb was reached at a frequency below 200 c.p.m. Shaking at this frequency resulted in the largest displacements of the fruit achieved at any frequency. However, due to the low speed, inertia forces were too small to be effective in fruit removal.

At high frequencies of 800 c.p.m. or above, the motion at the end of the limb became smaller. The large inertia mass of fruit and the damping due to leaves and small limbs vibrating out of phase restricted the motion at the free end of the limb and caused simple bending in the limb at the point of attachment of the clamp.

Detachment efficiency was reduced at high frequencies due to the acceleration isolation provided by apples supported on long willowy branches. High frequency shaking was also accompanied by a much heavier leaf fall than lower frequency shaking.

Spur Removal

Spur counts were similar to those for hand picking and averaged about 6 percent.

Table 1. Apple removal efficiency, spur damage, and inertia shaker frequency for Jonathan apple trees, October 9 to 13, 1967

Run	Length of limb	Base diameter	Clamp location (X/L)	Diameter at clamp location	Frequency	Length of shake	Fruit removed	Fruit removed per second	Strokes	Spurs	Shaker stroke	Limb-shaker displacement ratio	Acceleration on fruit
	Feet	Inches	Number	Inches	C.p.m.	Seconds	Percent	Percent	Number	Percent	Inches	Number	g's
1---	17	9	0.29	---	177	5.0	54	10.8	---	1.0	0.70	---	---
2---	16	8	.44	6	250	3.0	67	22.3	12.5	---	1.25	0.29	0.37
3---	14	6	.14	5	275	4.0	80	20.0	18.4	---	.65	1.00	.71
4[1/]---	18	7	.28	6	400	5.8	97	16.7	---	---	1.30	---	---
5---	15	7	.33	6	450	3.8	95	25	---	---	1.20	---	---
6---	12	6	.25	6	477	4.1	92	22.4	---	8.0	.55	---	---
7---	18	7.25	.28	6	480	3.5	98	28.0	28.0	5.6	1.25	1.30	5.25
8---	15	6.5	.33	5.5	500	3.7	96	26.0	30.8	6.1	1.20	1.00	3.0
9---	12	7	.50	6	580	3.4	93	27.3	32.8	8.0	1.1	2.40	12.7
10---	18	8.5	.45	6.5	777	4.3	75	17.4	---	6.0	.95	---	---
11---	18	7.5	.38	6.0	790	4.5	92	20.2	---	8.7	1.00	---	---
Average	15.7	7.3	.33	6.0	---	4.1	85	21.5	---	6.2	1.01	---	---

1/ Positive displacement shaker.

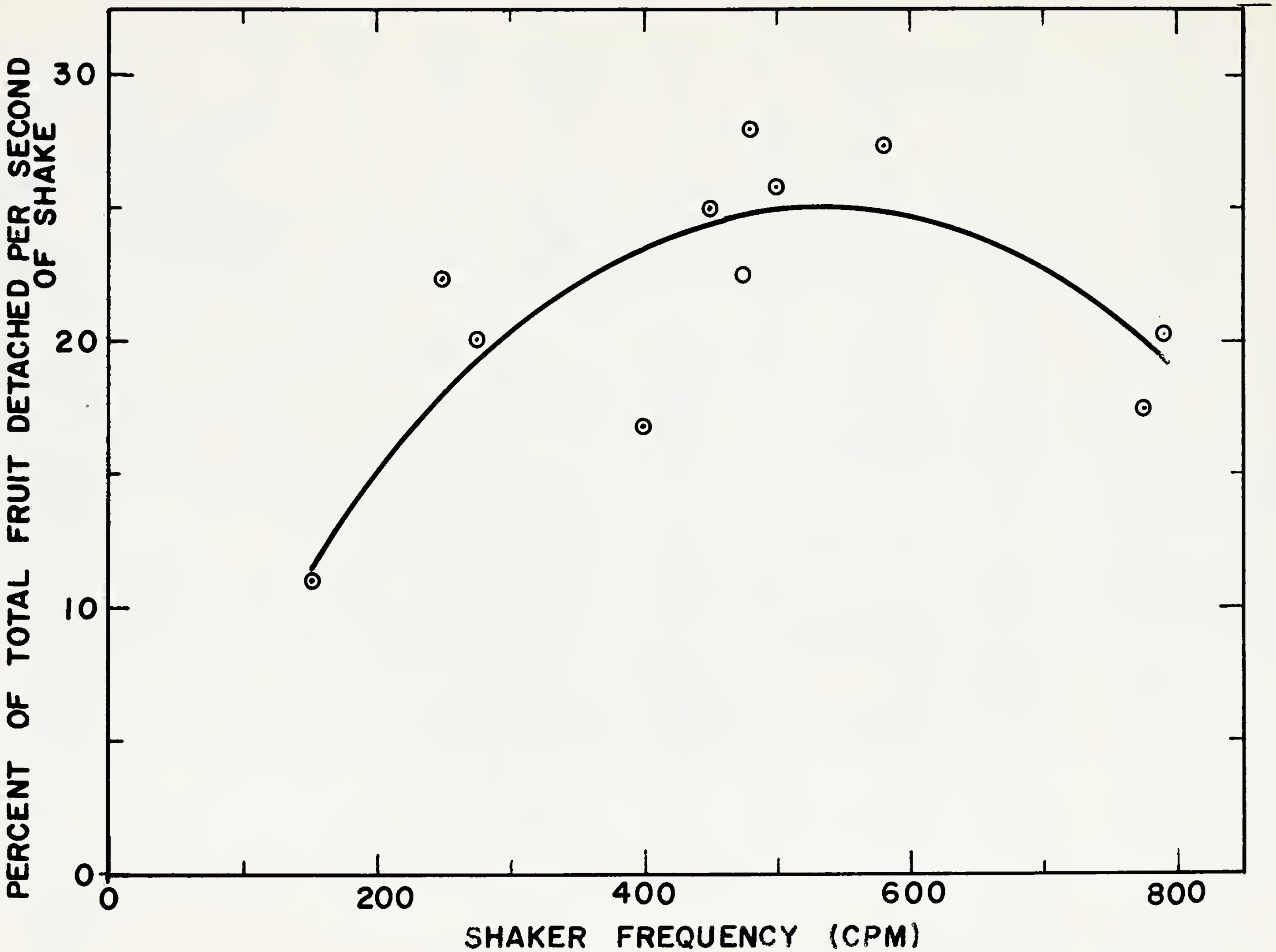


Figure 4. Detachment effectiveness as related to shaking frequency on Johnathan apples.

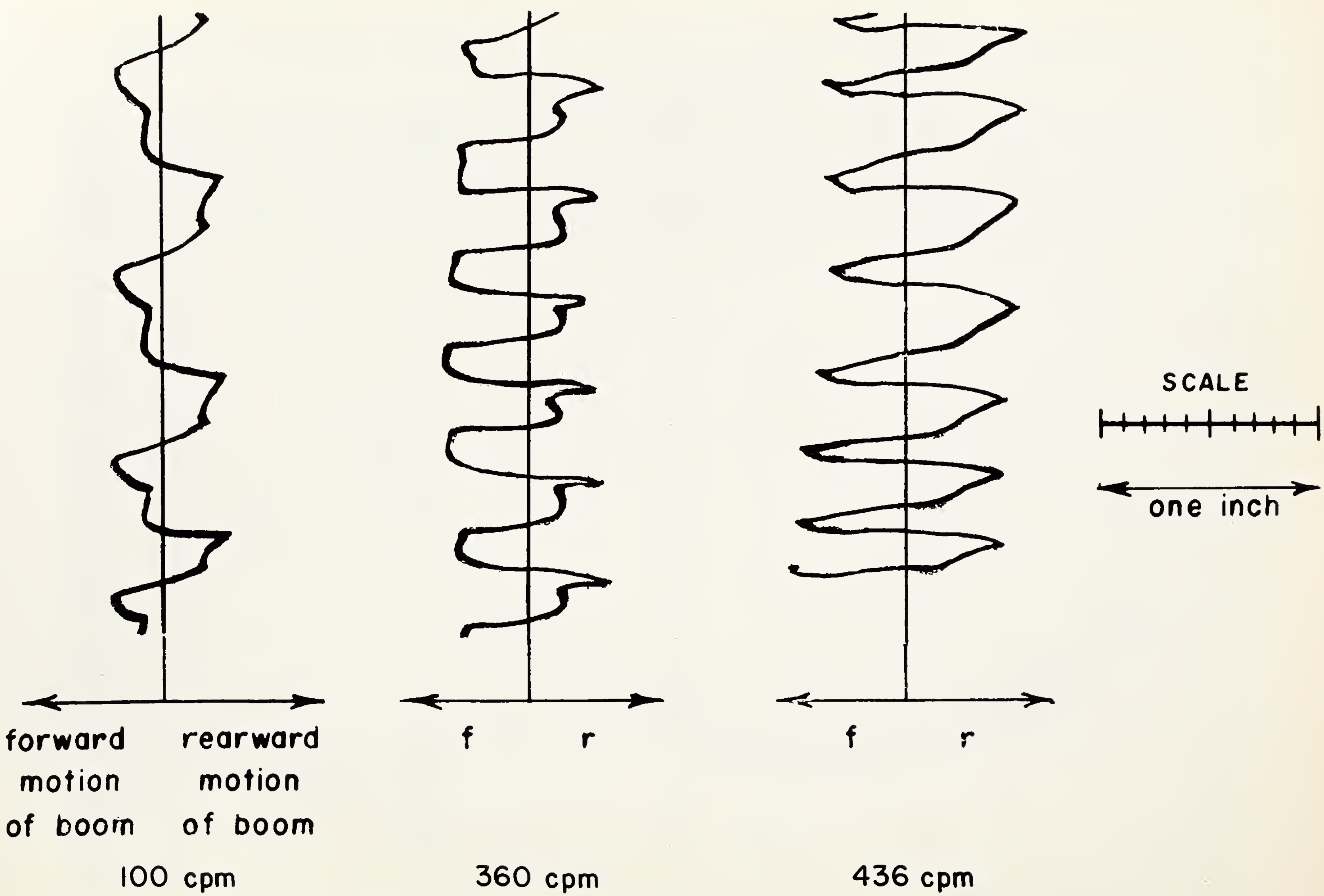


Figure 5. Typical displacement graphs obtained from the clipboard mounted on an inertia shaker boom.

CALCULATIONS

After the proper frequency range is established, based on the fruit and supporting system, the optimum stroke can be calculated. The stroke calculation is based on the shaking frequency, the number of acceleration g's necessary to remove the fruit, and the efficiency of the limb in transmitting the required stroke to the fruit. If the stroke is too small, shaking will be ineffective; if the stroke is too large, shaking will cause unnecessary damage to the fruit and its supporting system, with no increase in shaking efficiency.

Acceleration Force

The acceleration in g's necessary to remove the fruit was given by Adrian and Fridley(1) from the relation $F = W\,a/g$ as follows:

$$g's = F/W \qquad \text{--1}$$

where F is the detachment force and W is the weight of the fruit. (See table 2 for F/W ratios needed to remove various fruits.)

Table 2. Removal force, weight, and F/W ratio[1/]

Fruit	Harvest date 1967	Diameter	Removal force (F)	Weight (W)	F/W ratio (removal g's)
		Inches	Pounds	Pounds	Number
Apples:					
McIntosh---------	9/28	2.73	4.5	0.371	12.1
Cortland---------	9/28	2.75	5.2	.392	13.3
Jonathan---------	10/19	2.55	4.4	.288	15.3
Northern Spy-----	10/19	2.79	9.6	.403	23.8
Apricots:					
Montgamet--------	8/2	1.44	.89	.064	13.8
Blueberries:					
Jersey-----------	8/18	.35	.25	.001	250.0
Cherries:					
Montmorency------	7/28	.83	.22	.010	22.0
Peaches:					
Red Haven--------	8/16	2.76	6.0	.396	15.2
Elberta----------	9/20	2.78	3.4	.404	8.4
Plums:					
Stanley Prune----	9/7	1.59	1.8	.078	23.1

1/ Force and weight values given by Quackenbush, Stout, and Ries (6).

Limb Transmission Efficiency

The efficiency of the limb in transmitting the stroke to the fruit determines the effectiveness of the shaker. Therefore, in calculating the required shaker stroke, based on the number of g's for fruit removal, the limb efficiency must be considered.

Typical data for the three types of shakers tested are shown graphically in figure 6. The bottom curve gives the acceleration in g's at the shaker clamp, and the top curve, the acceleration at the end of the limb. Note that the acceleration at the clamp are similar in shape to those of displacements shown in figure 5. Note also that the acceleration at the end of the limb is sinusoidal, except for superposed effects of smaller vibrating limbs (fig. 5a), or from abnormalities in the shaker motion (fig. 5b and 5c).

The ratio of acceleration at the end of the limb to the acceleration of the limb efficiency is plotted in figure 7. This ratio is generally less than one due to bending of the limb between the clamp and the end of the limb. The amount of bending is determined by the limb stiffness, leaf damping, and mass of the limbs and fruit. In these tests, limb efficiency in the 400 to 600 c.p.m. range was about 63 percent.

Theoretical Limb Stroke Required for Horizontal Shake

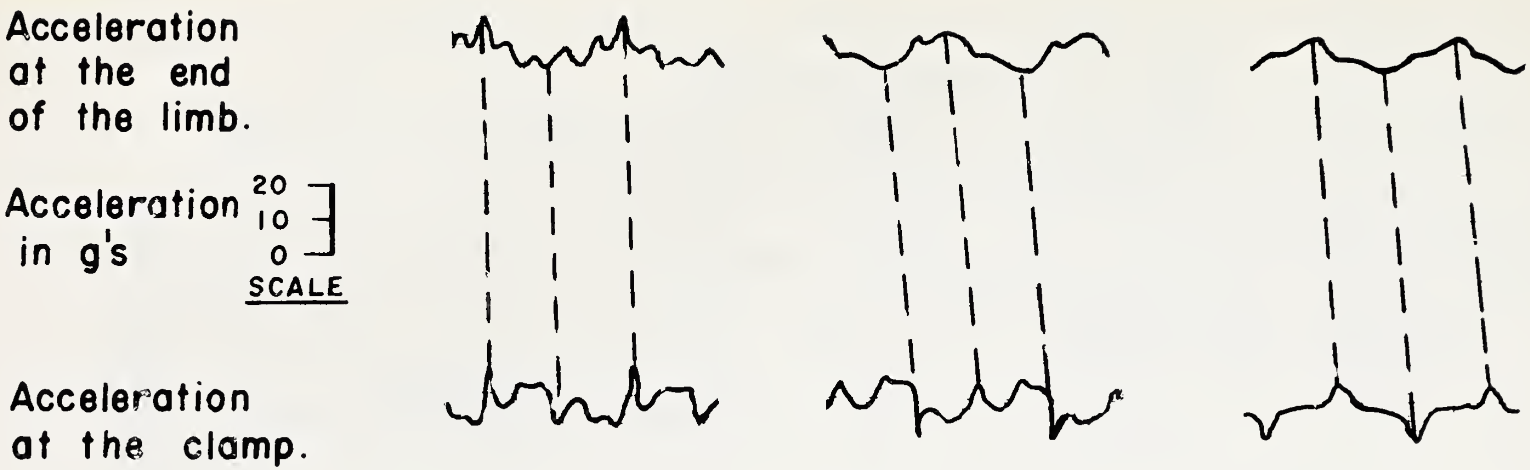
The required shaker stroke, S, for Jonathan apples can be calculated using frequency (F=500 c.p.m.), detachment acceleration (F/W=15.3 g's), and limb transmission efficiency (LE=0.63). Since the main force is exerted in the horizontal direction, the fruit weight, 0.288, must be added to the detachment force and must be increased by this amount. The F/W ratio becomes 16.3 g's. The stroke is then calculated from equation 1 by relating the peak acceleration transmitted by the shaker to the fruit as follows:

$$S = \frac{2(386)\ (3600)\ (F/W)}{(2\pi)^2\ (f^2)\ LE} = \frac{4.59}{0.63} = 7.3 \text{ inches}$$

Theoretical Limb Stroke Required for Vertical Shake

To calculate the theoretical limb stroke required for vertical shake, the same limb efficiency is used as for the calculation of the horizontal shake. (See positive displacement shaker, fig. 7)

For an F/W ratio of 15.3 and frequency of 500 c.p.m., the stroke $S = \frac{4.32}{0.63} = 6.85$ inches. This is 0.45 inches less than is required in horizontal shaking. Another major advantage of a vertical shake is that fruit detachment should be much easier from long hangers. In horizontal shaking, long hangers act as vibration isolators for the fruit.



SHAKER	a – large inertia	b – small inertia	c – positive displacement
length of limb (L)	18'	16'	18'
base diameter d_b	8"	7"	7"
clamp location (x/L)	0.333	0.333	0.278
diameter at clamp	7"	6"	6"
frequency	466cpm	477cpm	490cpm
peak stroke	1.1"	1.1"	1.25"
peak acceleration at clamp	9.3g's	9.3g's	9.9g's
peak acceleration end of limb	8.3g's	6.8g's	5.3g's

Figure 6. Samples of one test of acceleration at clamp locations and at the end of the limb for three models of limb shakers.

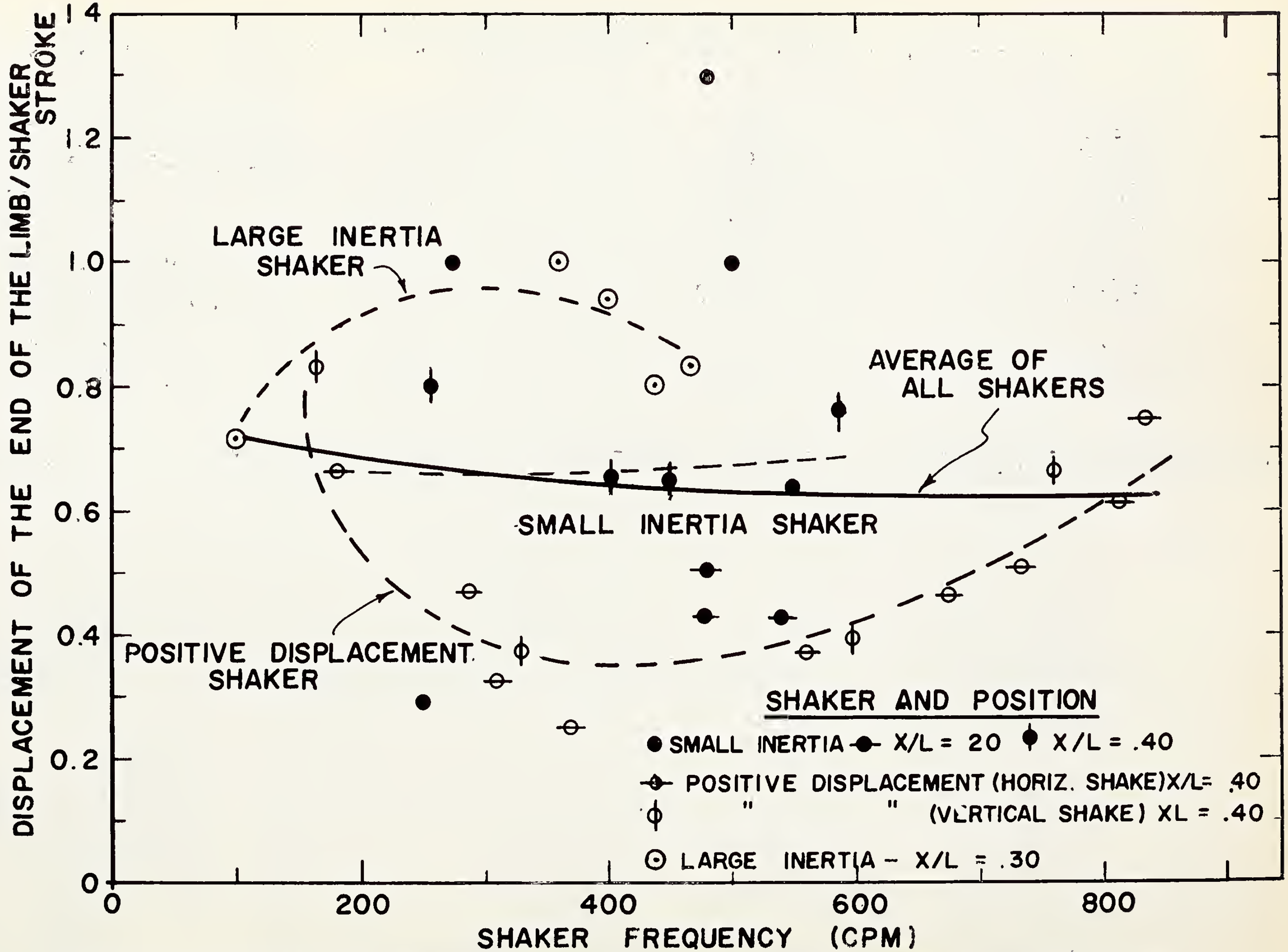


Figure 7. Efficiency of the limb in transmitting the shaker stroke to the end of the limb.

Practical Required Stroke

The theoretical limb strokes, discussed above, were calculated on the assumption that fruit would be removed in the first push of the shaker. Normal shaking would probably take 3- to 5-seconds and involve 30 to 90 oscillations. However, fruit is detached with a considerably smaller stroke as a result of fatigue failure.

Stroke values based on fatigue failure may be reduced by an estimated 30 to 50 percent in a stroke range of 3 to 5 inches. Further research is planned during 1968 to determine the optimum practical strokes.

Shaker Design Requirements

Since inertia shakers attach to and become part of the vibrating limb, the mass of the shaker parts must be included in the calculation of optimum stroke. If a positive displacement shaker is to be built, it should have the power to produce a 3- to 5-inch stroke. Limb motion, using a positive displacement shaker, was given by Wang (8) and Monroe and Wang (5). In their solutions, shaker motion was superposed on the base of a vibrating cantilever beam.

Effect of Crank Arm-Connecting Rod Ratio

In inertia shakers, the limb displacement depends on the peak acceleration of the inertia mass as follows:

$$a = M\omega^2 \; (1+M/L)$$

where a is the peak acceleration of the inertia mass, M is the shaker mass, ω is rotations per minute, and L is the length of the connecting rod. Thus, the acceleration and stroke are increased by the factor of (1+M/L).

Shaker Mass and Crank Throw Required for Desired Stroke

To produce desired stroke, S, at the limb, requires the proper relation of limb mass, $M_{EQ}(L)$, the shaker unbalance mass, M_u, boom mass, M_b, limb stiffness, K_{11}, internal limb damping, $K_{11}\tan\delta$, external limb damping due to flexure of the limb, leaves, and small limbs, and the crank throw, S_c.

This relation is given in various forms (1, 2, 4) and is shown in the force diagram in figure 8.

By summing the horizontal forces in figure 8, we have the relation

$$S = \frac{S_c \; W_u \; \cos\theta}{C(\omega) + W_b + W_u} \qquad \text{--2}$$

where

$$C(\omega) = \frac{386 \; (\omega^2 M_{EQ}(L) - K_{11})}{\omega^2}$$

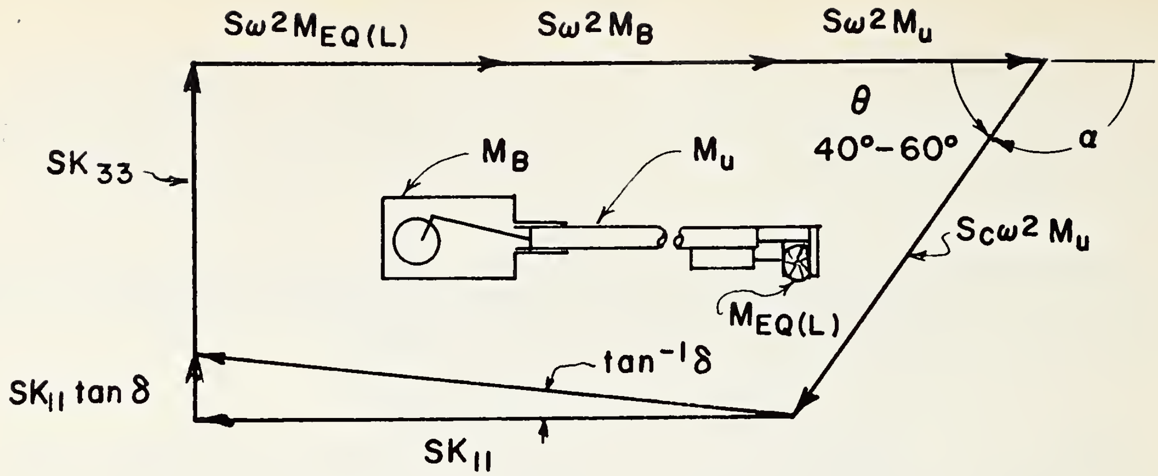


Figure 8. Force relations in an inertia shaker. ω, frequency in radians per second; M_B, mass of boom; M_u, unbalance mass of shaker; $M_{EQ(L)}$, equivalent mass of limb; K_{33}, external damping of limb; $K_{11}\tan\delta$, internal damping of limb; S, absolute displacement of limb; S_c, absolute displacement of crank stroke.

For limbs of a particular size, being shaken at the same frequency, $C(\omega)$ is a constant and can be calculated by using any shaker on the desired limb. When the phase angle approaches 180°, $\cos\theta$ goes to zero and $C(\omega)$ reduces to $W_{EQ(L)}$. This relation is then the same as that given by Adrian and Fridley (1). The relation given by Lenker (4) is similar to equation 2 but considers the force in the boom in place of the limb mass and stiffness components. If the boom forces are known, the limb mass and stiffness components are the most convenient relations to use.

From data given by Adrian and Fridley (1), a phase angle of zero to 60° or values of x from 120° to 180° could be expected.

SUMMARY AND CONCLUSIONS

A study was conducted to determine the most effective frequency of shaking for harvesting Jonathan apples. Considerations were given to fruit detachment force, limb efficiency of transmitting vibrations, and inertia shaker design. The following conclusions may be drawn:

1. The most efficient separation of Jonathan apples occurred at frequencies of from 400 to 600 c.p.m.
2. Strokes of 4 to 5 inches at the fruit stem probably would be necessary to remove Jonathan apples at 400 to 600 c.p.m.
3. Limb efficiency in transmitting the shaker stroke to the end of the limb averaged about 63 percent. A shaker stroke of 7 inches would thus be required to remove the fruit in the first push.
4. The actual stroke required, however, is probably not 7 inches but 3 to 5 inches, due to fatigue failure of the stem. During shaking for 3 to 5 seconds, the fruit is oscillated about 30 to 40 times.

5. In shaker design, if the ratio of crank eccentricity to rod is 0.10 or larger, the stroke should be calculated using the equation $S = r\ (1 + r/L)$.

ACKNOWLEDGEMENT

The authors wish to thank Richard J. Wolthuis, mechanical engineering technician, USDA, for his help in collecting and analyzing the data, and Mr. Herbert Teichman, owner of Skyline Orchards, Eau Claire, Michigan, for providing the orchard facilities.

LITERATURE CITED

(1) Adrian, P. A., and Fridley, R. B.
1965. Dynamics and Design Criteria of Inertia-Type Tree Shakers. Amer. Soc. Agr. Engin. Trans. 8(1): 12-14.

(2) Diener, R. G., Levin, J. H., and Tennes, B. R.
1967. Directional Strength Properties of Cherry, Apple,and Peach Bark and Influence of Limb Mass and Diameter on Bark Damage. Amer. Soc. Agr. Engin. Paper 67-820, 8 pp.

(3) _____ Mohsenin, N. N., and Jenks, B. L.
1965. Vibration Characteristics of Trellis-Trained Apple Trees With References to Fruit Detachment. Amer. Soc. Agr. Engin. Trans. 8(1): 20-23.

(4) Lenker, D. H., and Hedden, S. L.
1966. Limb Properties of Citrus as Criteria for Tree Shaker Design. Amer. Soc. Agr. Engin. Paper 66-637, 21 pp.

(5) Monroe, G. E., and Wang, Jaw-Kai.
1967. Systems for Mechanically Harvesting Coffee. Amer. Soc. Agr. Engin. Trans. 2(2): 270-278.

(6) Quackenbush, H., Stout, B. A., and Ries, S. A.
1962. Pneumatic Tree-Fruit Harvesting. Part I. Agr. Engin. 43(7): 388-393.

(7) Studer, H. E.
1966. Motion of Pendular Fruit Systems During Vertical Vibration. Amer. Soc. Agr. Engin. Paper 66-635, 11 pp.

(8) Wang, J. K.
1965. Mechanical Coffee Harvesting. Part A. Amer. Soc. Agr. Engin. Trans. 8(3): 400-405.

UNITED STATES DEPARTMENT OF AGRICULTURE
AGRICULTURAL RESEARCH SERVICE
BELTSVILLE, MARYLAND 20705

OFFICIAL BUSINESS

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF AGRICULTURE